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Submitted
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THE ANALYSIS OF STRUCTURALLY ORTHOTROPIC SHELLS BY MEANS OF THE COMPLIANCE METHOD

I. Introduction

The object of this report is to state the six month progress on NASA Grant NGR 44-001-031, Supplement No. 1. The grant in turn is a renewal of NASA Grant NGR 44-001-031. The current grant has four objectives.

1. Extend compliance studies to general shell configurations with general type reinforcements.
2. Program the compliance equations to account for stiffeners not amenable to simple algebraic analysis.
3. Initiate a limited testing program for stiffened shallow shells in order to experimentally verify the compliance equations.
4. Perform a non-linear analysis for shallow shells in order to determine the non-linear compliance equations.

At present, the greatest effort has been directed toward objective number three. However, all of the objectives have been acted upon in varying degrees of effort, though none have been brought to a state of completion. A detailed discussion of the results obtained for each of the listed objectives is given in the following portion of the report.

II. Discussion of Results

1. First Objective

At the present time, compliance studies are being completed for reinforced cylindrical shells. The elastic constant compliances

for a rib stiffened cylindrical shell have been completed as part of a doctoral dissertation. The compliance criteria developed in the dissertation are presently being extended to other type reinforcements.

The only means of checking a compliance study for a particular reinforcement is to develop in detail the shell equations for a particular reinforcement. Comparison of the solution of these equations to those obtained from the orthotropic equations whose elastic constants have been determined from some compliance criteria establishes the applicability of the criteria.

As stated in a previous paragraph, a compliance criteria has been determined for a rib stiffened cylindrical shell and this criteria is under investigation for its applicability to other type reinforcements. Since sandwich construction is an extremely important type of shell reinforcement, the compliance criteria also should be extended to this type of reinforcement.

In order to determine whether the compliance criteria is applicable to sandwich shells, a detailed analysis of a sandwich reinforced shell is under investigation as part of a doctoral dissertation. However, in analyzing such a shell, a number of assumptions customarily utilized are being relaxed in order that the analytical and also numerical results yield the best possible values. In particular, the normal strains, stresses and transverse shear stresses are included in the core though the facing sheets will still be subject to customary first order analysis.

2. Second Objective

Until the compliance criteria discussed in the previous section has been verified, little can be done in programming the general compliance equations. However, in the case of the shallow shell, the compliance relations for the bending rigidities of a rib type reinforcement can be programmed since these results are based on Huffington's work. These rigidities are in process of being programmed.

3. Third Objective

The testing program that has been initiated is directed toward the experimental verification of the analytically derived compliance equations for stiffened shallow shells. Because of the absence of facilities for such testing, Texas A&M University has contributed \$23,335 for the purchase of equipment. A detailed list of this equipment is given in Table 1.

It is anticipated that the experimental portion of compliance shell analysis will be extended to include general shell configurations and dynamic and non-linear shell responses. As a consequence the equipment purchased has been chosen so that it will suffice for the immediate task and yet be applicable to future testing programs.

The immediate objective of the testing program is the determination of the membrane rigidities for a longitudinally rib stiffened cylindrical panel. At the conclusion of the previous grant,

NGR 44-001-031, the orthotropic shallow shell equations had been derived and applied to a simply supported rib reinforced cylindrical panel as shown in Fig. 1. The elastic orthotropic constants were shown to be grouped so that one grouping reflected the bending rigidity of the shell while the second grouping reflected the membrane rigidity. The compliance between the rib stiffeners and the bending rigidities was based on Huffington's compliance relation between the rib stiffeners and the membrane rigidities remained indeterminate.

Two possible solutions for the membrane rigidities were investigated. The first possible solution was based on a consistent definition of the elastic constants. Since the membrane and bending rigidities consisted of groupings of the same elastic constants, a relation was derived relating the two rigidities. Letting C_{ij} and D_{ij} represent the membrane and bending rigidities and letting h represent the shell thickness, it was found that

The second possible solution was based on the fact that the load resistance mechanism of a shallow shell structure differed but slightly from that of a plate. Since the linear analysis of a plate precluded the inclusion of the membrane forces, it seemed reasonable to assume that for small shallowness ratios, the membrane effects on a shallow shell also would be small. Hence, though

the second solution did take into account the curvature of the shell and therefore the membrane effects, it did neglect the contribution of the rib reinforcements to the membrane rigidity.

The maximum deflections as predicted by the two solutions were plotted against the radius of the shell and are given in Fig. 2. Since the length and width of the panel were assumed to be constants of 30" and 25" respectively, then increasing radius indicated increasing shallowness.

Inspection of Fig. 2 revealed that the two curves differed greatly in deflection as the radius was decreased. Since each of the curves could be justified in a rational manner only an actual test would determine which of the two solutions was realistic.

The testing procedure will consist of experimentally determining the maximum deflection of a rib stiffened aluminum cylindrical panel. The panel will be simply supported and the external loading will be a uniform pressure exerted normal to the shell surface.

The model consists of a rolled aluminum sheet and a series of thin aluminum beams. These beams are the ribs of the model and are epoxy glued to the upper and lower surfaces of the aluminum sheet. The dimensions of the rolled sheet, ribs and composite figure are given in figures 3,4,5.

The model is supported on a bed which also provides the simple support conditions. The lateral edges of the shell are free to rest on shelves which in turn are attached to the bed. Circumferentially, the edges of the shell rest on curved end plates and

are attached to these end plates by means of thin flexible cables whose tension is adjusted by means of turnbuckles. In anticipation of future tests, though the shelves supporting the lateral sides of the shell are fixed to the testing bed, the end plates are readily removable in order to accommodate other end plates and hence cylindrical panels of varying curvature. The bed, end plates and shelves are shown in Fig. 6.

Shell loading is provided by means of a vacuum pump. The volume enclosed by the specimen and test bed is evacuated and thereby causing a differential pressure to exist between the outer and inner surfaces of the panel. Thus equivalently, a constant normal surface load occurs as on external excitation. In order to obviate pressure surges from the vacuum pump, a vacuum chamber is installed between the pump and test bed. Gage pressures are measured by means of a manometer attached to the bed. Fig. 7 illustrates the test bed, end plates, vacuum pump and chamber and the manometer.

Deflection measurements are taken along the line of symmetry of the shell panel. Though these deflections are small, their magnitude still lies within the realm of a dial gage. Hence, dial gages mounted on extension arms which in turn are mounted to magnetic blocks are the primary deflection measuring device. The resulting test apparatus including the test specimen is shown in Fig. 8.

At the present time, the test bed is completed. All the necessary equipment such as vacuum pump, vacuum chamber, dial

gages have been ordered and delivery is anticipated within the month of June. The test specimen as previously described is under construction at the Manned Spacecraft Center, Houston, Texas, and its delivery also is expected within the month of June.

4. Fourth Objective

The non-linear compliance equations require an understanding of the general non-linear phenomena associated with thin elastic shells. However, such an understanding as yet is not in evidence. Though the literature abounds with non-linear shell theory formulations, most of the resulting equations are stated in tensorial form.

The tensorial representation of the shell equations possesses important properties. However, the applicability of these equations to a formulation of a solvable set of shell equations is minimal. The primary reason for this condition is that the tensorial representation, when expanded, yields a too general set of non-linear differential equations whose solution cannot be approximated either analytically or numerically. More importantly, the physical significance of many of the terms which describe rotations or elongations are obscured by the contracted tensor notation.

In order to preserve the physical significance of the non-linear terms, various authors have developed non-linear shell theories in terms of physically measurable parameters. However, faced with the complexity of the general non-linear formulations, various approximations to the extent of the non-linearities have been introduced. The net result is a series of non-linear shell theories, the theories graduated such that each successive

theory attempts to account for a non-linear phenomena discounted on the preceeding theory.

The graduated attempt at non-linear shell theory is a logical method of dealing with non-linear shell phenomena. However, even in such a step wise formulation of the shell equations, basic inconsistencies result, especially in the expressions for the torsion and curvature change of the shell reference surface. Unless these bending and twisting parameters are completely defined, and defined in terms of physically measurable quantities such as strain and rotation, any approximation to a non-linear shell formulation will be subject to error.

The membrane strains, curvature changes, torsion and compatibility equations are completely defined by the first and second quadratic forms of the deformed reference surface of the shell. Hence any simplification of these quantities must begin with an investigation of these two fundamental forms. In particular, if these two basic forms can be expressed solely in terms of physically measurable quantities such as rotations and membrane strains, then simplification of the shell equations can be identified with the neglect of the effects of some physical parameter.

At the present time the non-linear expressions for the first and second quadratic forms are being investigated. In particular, the work is being directed toward a physical interpretation of the coefficients of these two forms. The results of the investigation will be used as part of a doctoral dissertation.

Table 1 - Major Laboratory Equipment

1. Electro-optical displacement measuring device

Physitech Model 39 Electro-Optical Tracking System

2. Electro-optical strain measuring system

Physitech Model 39 complete with lenses, tripoid and
reflex viewers

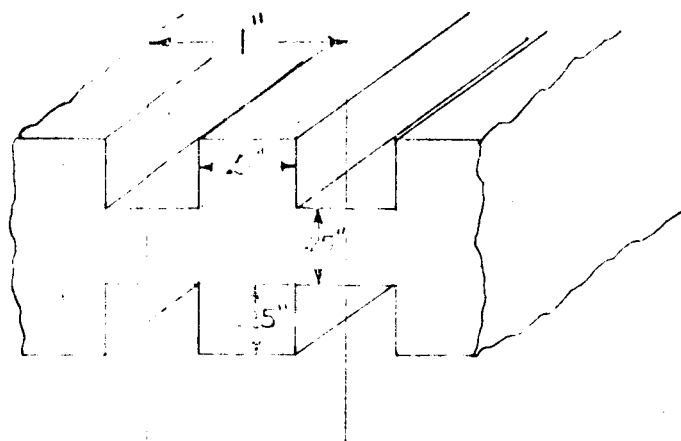
3. Strain gage read out equipment

Binary Electronics Corp. Model 306B

4. Strain gage digital recorder

Binary Electronics Corp. Model 206B

REPEATING SECTION OF HOLLOW SHELL



COMPLETE SHE

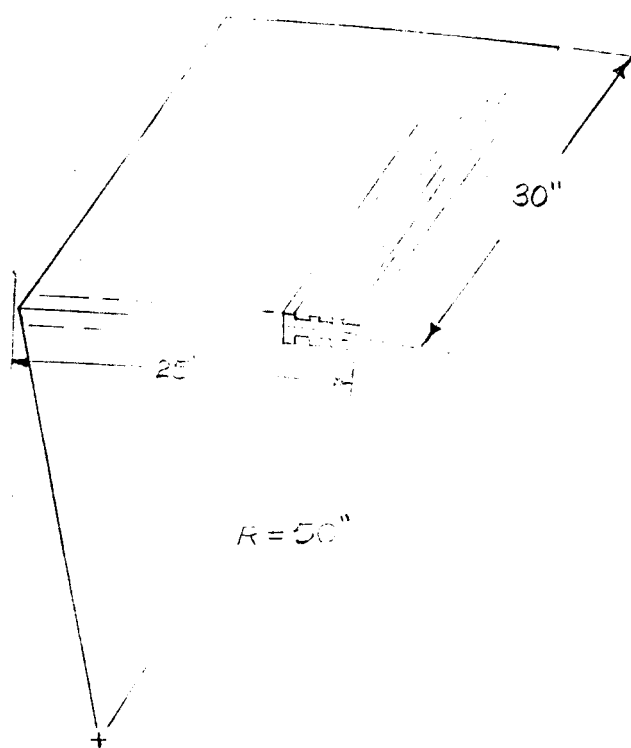


Fig. 2 - Analytical reinforced shell segment

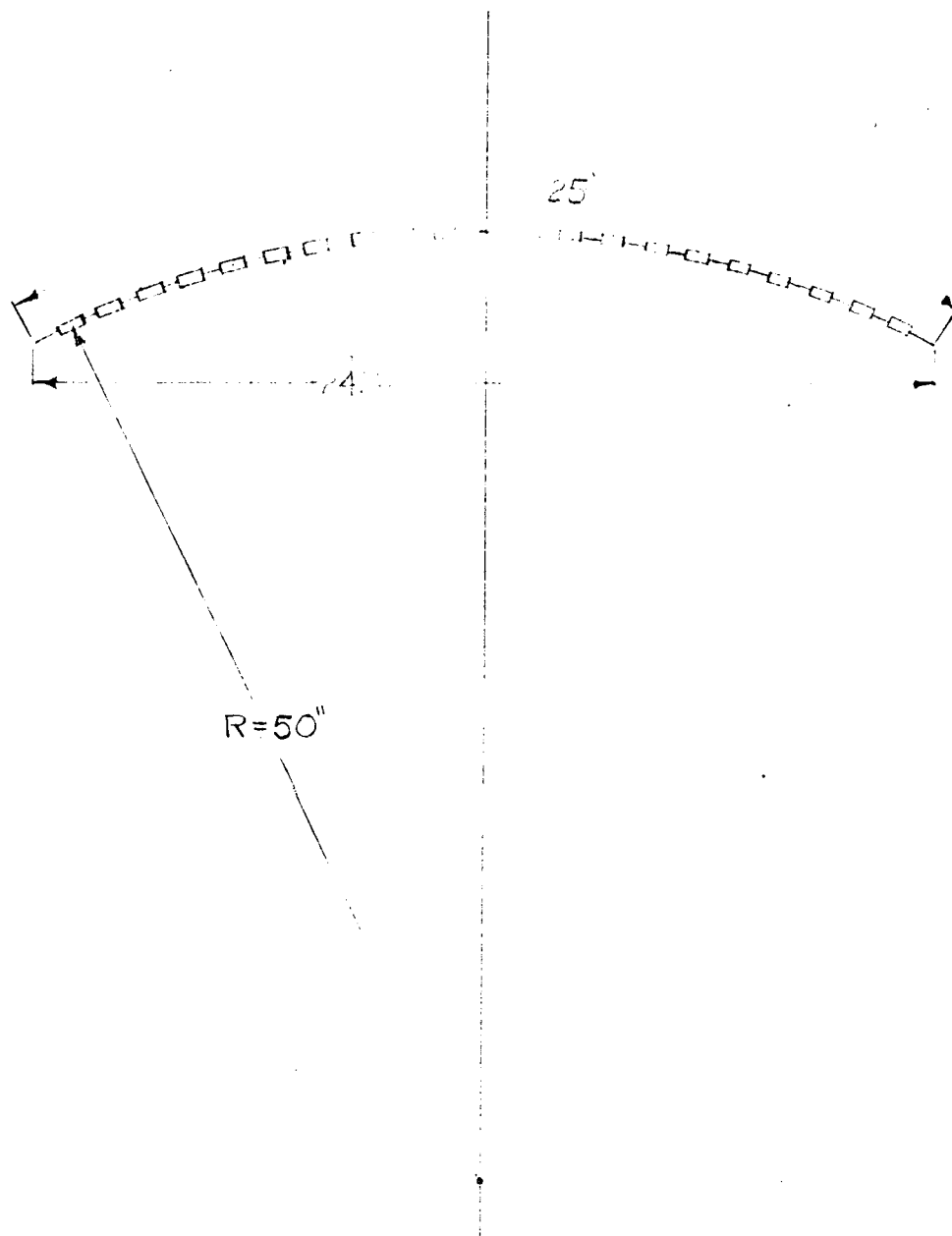


Fig. 3 - End view of test specimen

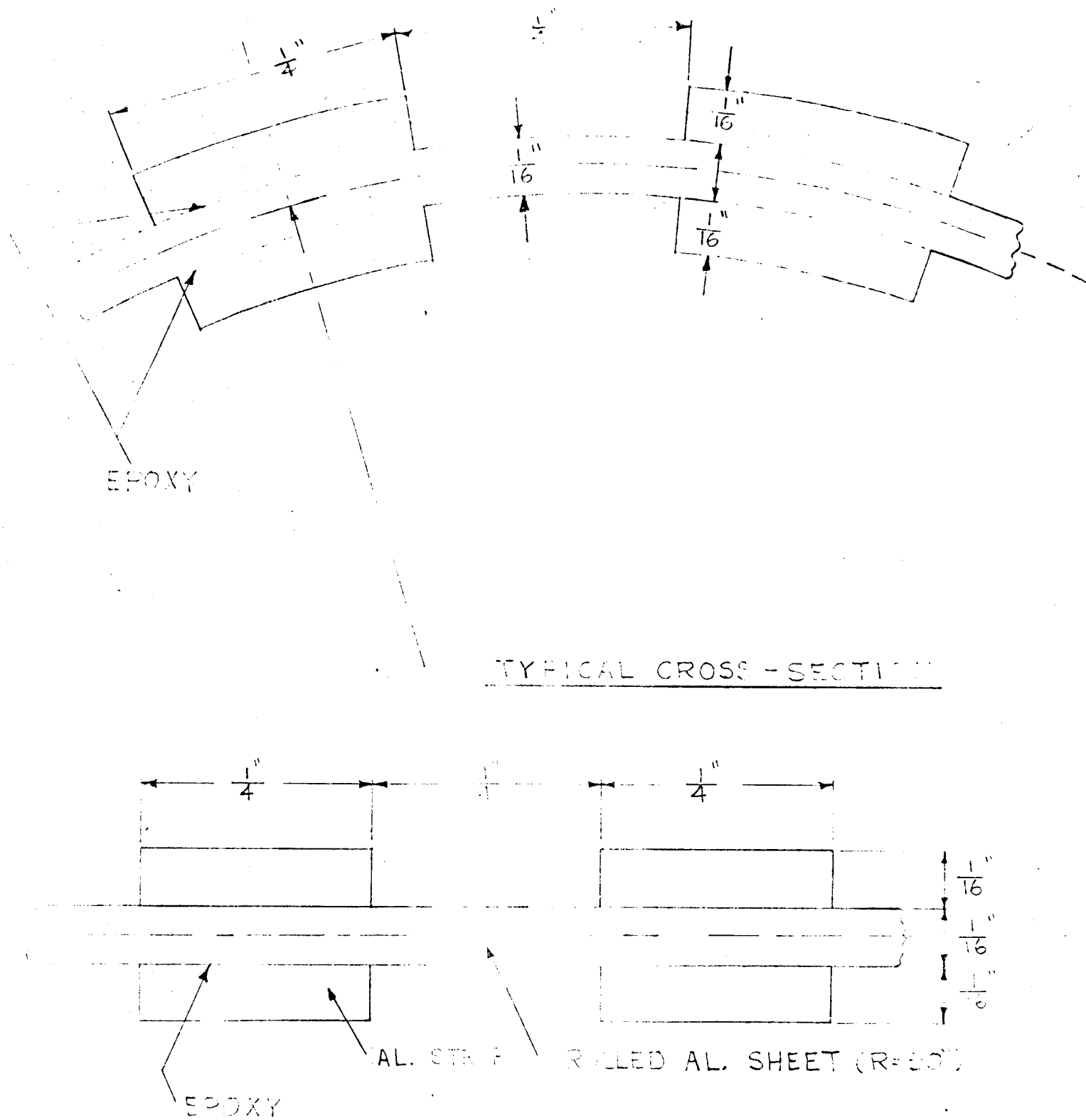


Fig. 4 - Detailed view of rib reinforcements

SECTION AT EDGE

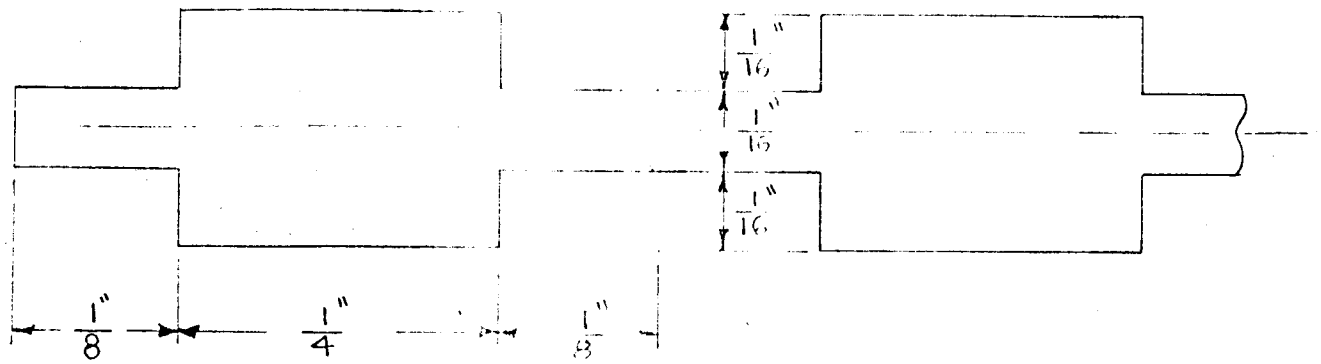


Fig. 5 - Detailed view of edge of specimen

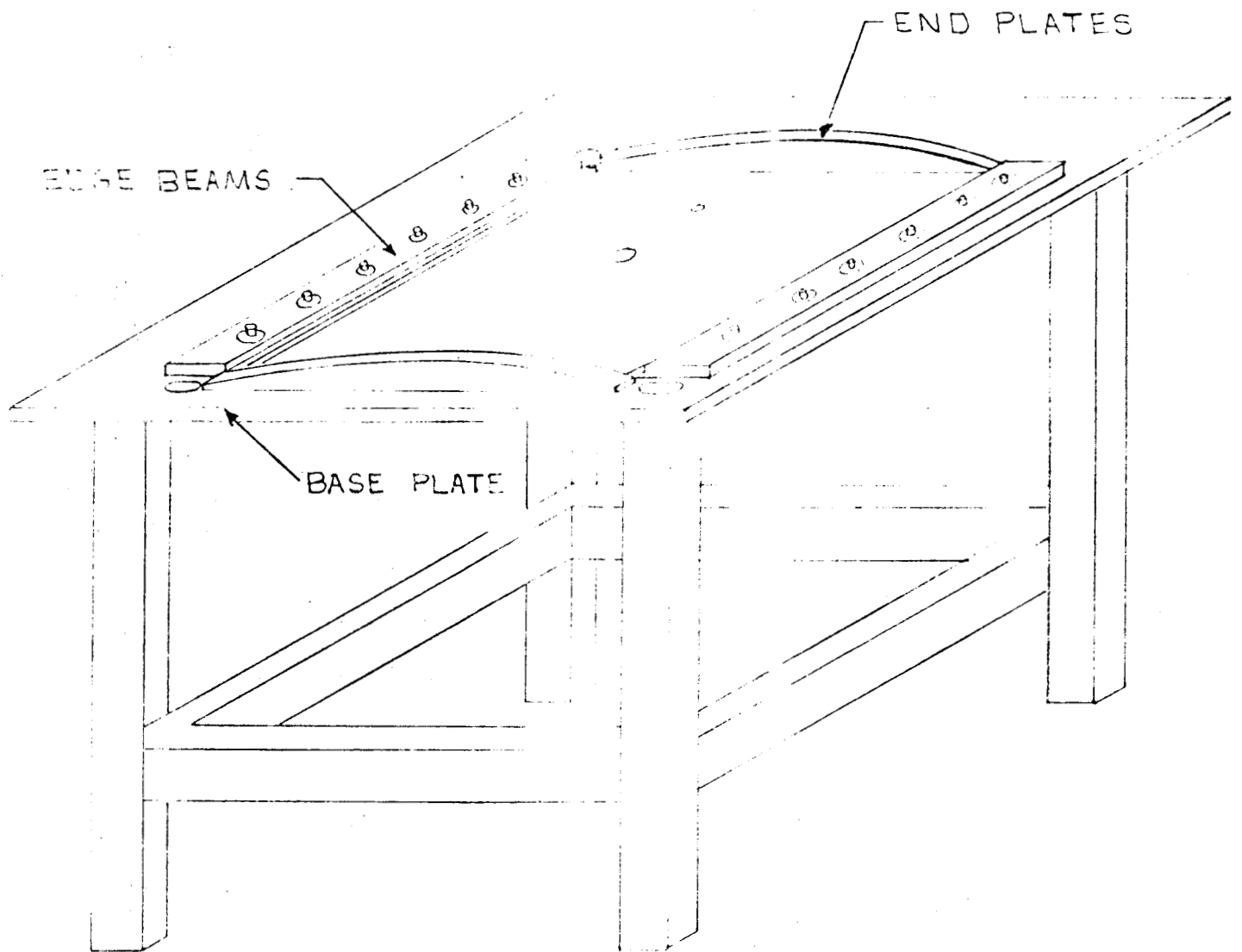


Fig. 6 - Isometric view of test bed and end plates

